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Reduction of CO_2 emissions by improved management of material and product use: the case of transport packaging

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Abstract

About 40% of the global primary energy use and emission of CO_2 is related to the production of materials. In this study we investigate the potential and cost-effectiveness of CO_2 emission reduction by means of improved management of material use for transport packaging in Western Europe. Measures for improved use of transport packaging material are identified and evaluated. A supply curve for CO_2-emission reduction is presented based on data about the use of transport packaging in 1995. We show that technically it seems possible to reduce the CO_2 emissions related to the production and use of transport packaging in 1995 by 40% when new packaging technology is implemented that is expected to become available between 1995 and 2010. In this reduction figure, improvement of energy efficiency in material production processes and changes in packaging demand are not taken into account. Most evaluated measures can be implemented cost-effectively, when taking life-cycle costs into account. This would result in a CO_2 emission reduction of 34%. Evaluation of the measures shows that a 12% reduction of CO_2 emissions related to transport packaging is possible by using lighter packages. Material substitution can lead to a reduction also of 12%. From a CO_2 emission reduction point of view, the most promising improvements are large changes in the packaging system like substitution of single use packaging by re-usable packaging. This may lead to a 16% reduction in CO_2 emissions.

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However, large-scale introduction of this option may be hindered by the complexity of implementation.

Keywords: Material use; Packaging material; Transport packaging; Material management; CO_2 emission reduction

1. Introduction

Many types of materials are used for the production of packaging, like glass, plastics, paper and steel. The production processes of these materials are energy intensive. The energy requirements for production of these materials vary from 20 GJ/t for packaging paper to 70 GJ/t for plastics and 187 GJ/t for aluminum [1]. The energy consumption and CO_2 emissions that are related to the production of these materials can be reduced by energy efficiency improvement in the production route and by improved material management.

To reduce the energy consumption and emission of CO_2, many studies focus on improvement of the energy efficiency of production processes. Improved management of materials, however, has had much less attention. Most material management studies that evaluate measures like material recycling, material substitution and product design focus on the effects on waste reduction.

There are a few studies that focus on the relevance of material use to reduce CO_2 emissions. In Ref. [2] the importance of materials as sources and sinks of CO_2 emissions is discussed. Less attention is given to ways and means to reduce the related CO_2 emissions. In Ref. [3] the same author concluded that "…the potential for emission reduction in the materials system seems to be of a similar magnitude as the emission reduction potential in the energy system". In 1998, EPA published a study on greenhouse gas (GHG) emissions from management of materials in municipal solid waste [4]. The study showed that management of materials presents many opportunities for GHG emission reduction. However, the focus of the study was on waste management; a detailed investigation of options for more efficient material management in the production and consumption stage was not carried out. Two studies from Utrecht University described how more efficient management of materials may lead to reduction in energy use. In Ref. [5] the potential of energy savings due to more efficient use of fertilizer was investigated for The Netherlands. In Ref. [6] an approach was described for analyzing the potential of material efficiency improvement which was subsequently tested on plastic packaging in The Netherlands. Both studies showed that there is a significant potential for reduction of CO_2 emissions by more efficient use of materials in those specific cases. Finally in Ref. [7] the United Nations Department of Policy Coordination and Sustainable Development stated the importance of material efficiency research in order to understand the potentials for emission reduction.

In an earlier study we already showed that more efficient use of primary packaging may result in significantly lower CO_2 emissions [8]. The objective of this study is to investigate options for more efficient use of all materials related to *transport* packaging in Western Europe and to calculate the CO_2 emission reduction potential when these options would be implemented. Information on the total material use and CO_2 emissions related to transport packaging in Europe has not been published in literature and is therefore part of the objective of this study.

In the next section we describe the method we use to investigate the options: this is derived from an approach presented by Worrell et al. [6]. In Section 3, we present the general input data we use in this study. In Section 4, the demand for transport packaging materials in Western Europe is analyzed. Section 5 elaborates on current packaging technology and possible measures to improve materials management. In Section 6 the potential reduction in CO_2 emissions is calculated and evaluated. We end with a discussion and conclusions.

2. Method

The method that we used for calculating the potential and cost-effectiveness of CO_2 emission reduction by improved management of materials used for transport packaging is identical to the method that we used for similar calculations on primary packaging. We will describe the method shortly. For a detailed description we refer to Ref. [8].

The method consists of six steps. First the current consumption of transport packaging is analyzed. Because many different packaging products exist, with a large variety in packaging characteristics, we group them in a number of categories. For the analysis we have selected the following six categories: (1) carrier bags, (2) industrial bags, (3) transport boxes, (4) grouping films, (5) pallets, and (6) transport films. We differentiate between transport films and grouping films because transport films are used to bundle packages on a pallet while grouping films are used to bundle smaller amounts of rigid packaging. For this reason, the strength requirements for grouping films are different than for transport packaging. We differentiate between carrier bags (for transport of final products by consumers) and industrial bags (for transport of intermediate and bulk products) for the same reason. The strength requirements for carrier bags are smaller than for industrial bags.

Second, reference packages are defined to model the wide variety of packages that exist within the defined categories.

Third, the lifecycle CO_2 emissions and the life cycle costs are calculated for the reference packages. This is done by summation of the CO_2 emissions and costs of the individual life cycle stages and transport between these stages. We discern the following stages: material production, packaging making, filling, unpacking, maintenance, waste collection, and waste management (Fig. 1). All CO_2 emissions and costs are calculated per specific function that all packages need to fulfil, also called the functional unit (f.u.). For all categories, except the category 'industrial bags', the functional unit is defined as 1000 transport trips. A transport trip is defined as the transport of a package (e.g. a transport box or pallet) plus packaged goods from the filling stage to the unpacking stage (Fig. 1). For industrial bags the

CO_2 emissions are calculated for transportation of 1000 kg of products in order to be able to compare packaging concepts with different volumes.

Fourth, we identify measures that lead to an improved use of materials in the life cycle of the reference packages. Improved use of materials considers all measures that lead to a reduction of CO_2 emissions in the life cycle of the package. In Fig. 1, these measures are presented by the dashed lines. Possible measures are the use of thinner materials, new product design that leads to a lighter package, product re-use, material recycling, and material substitution. New packages that are the result of these improvement measures are called *improved packages*. The characteristics of improved packages are based on recent developments in packaging

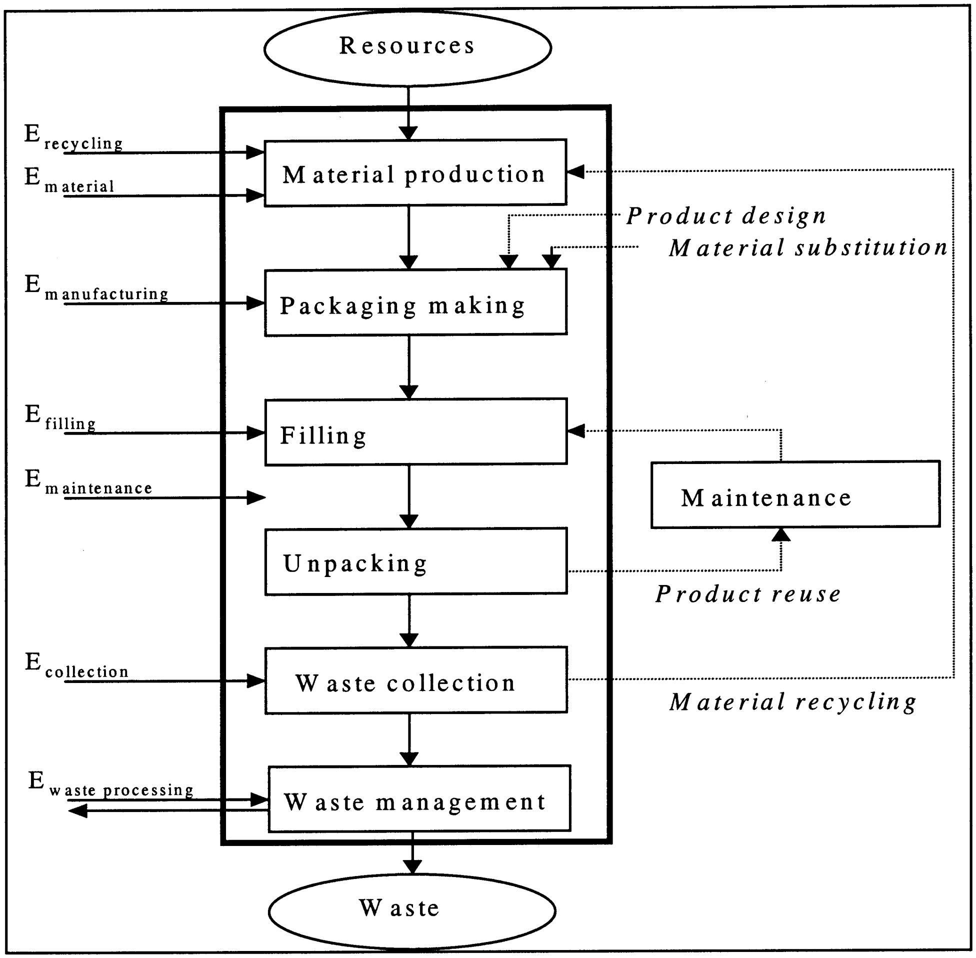

Fig. 1. Life-cycle of transport packaging. The simple life-cycle is depicted in the box, improvement options are depicted as dotted lines. On the left side the energy requirements of the different processes are stated. Unpacking is assumed to require no energy since it is not a mechanical procedure.

technology. Options are only taken into account if they are technically feasible in the short term or are already proven technology. The time horizon in this study is therefore set at 2010. 1995 is used as reference year.

In this study only improvements in *packaging* technology are taken into account. Other improvements that could reduce the CO_2 emission related to the production and use of packaging are not studied, e.g. improvement of energy efficiency of material production processes, energy efficient transportation systems, and changes in waste management technologies.

Fifth, the CO_2 emissions and the life cycle costs of the improved packages are calculated and compared to the standard packages. The CO_2 emission reduction potential is calculated by multiplying the difference in CO_2 emission between the improved and the reference package per functional unit by the number of functional units that correspond to the actual packaging consumption in the reference year.

Sixth, the cumulative CO_2 emission reduction is calculated for the situation where all measures are implemented. The measures are also evaluated in terms of cost-effectiveness. A supply curve is used for this evaluation[1]. Choices about the order of implementation are important because measures can influence the potential savings of each other, or even prevent the application of a specific measure. In Ref. [8] we partly based the ordering of improvement measures on the difficulty of implementation. A first assessment of the difficulty of implementation was made by assuming that the most critical factor that determines the difficulty of implementation, is the necessary change in the packaging system. This way of ordering proved to be helpful to create insights in the CO_2 emission reduction potential of a wide variety of improvement measures. In this paper we will also order the improvement measures by implementation difficulty. For construction of the supply curve the measures with low implementation difficulty are implemented first and measures with high implementation difficulty are implemented later.

The quality of the input data and the influences of the choices made in different stages of the method, e.g. definition of reference and improved packages and evaluation of measures, is discussed by means of a sensitivity analysis in the discussion.

3. General input data

To calculate the life cycle CO_2 emissions and life cycle costs of the reference and improved packages two types of data are necessary. First, specific data are necessary on the physical characteristics of the packages, e.g. weight, type of material, trip number and volume. These data are presented in the next section where we describe the characteristics of the reference and improved packages. Second, general data are necessary on energy use and costs of the different stages in the life cycle of the packages. These data are also described.

[1] See Ref. [6] for a detailed description of the construction of a supply curve for reduction of CO_2 emissions by improved material use of packaging materials.

Table 1
GER values for materials used for transport packaging per tonne packaging[a] [9–11]

	Feedstock ($GJ_{primary}$/t)	Primary energy ($GJ_{primary}$/t)	Electricity ($GJ_{electricity}$/t)	Total GER ($GJ_{primary}$/t)
PE	47.7	30.1	7.9	97.6
Recycled PE	0.0	0.6	0.6	2.1
PP	47.7	25.5	6.9	90.3
Recycled PC	0.0	0.6	0.6	2.1
PET	45.8	29.0	9.0	97.3
Corrugated board	18.6	6.0	8.2	45.1
Packaging paper	0.0	11.5	0.6	12.9
Sawn wood	15.6	5.3	0.8	22.8
Pressed wood fibers	17.3	7.4	0.3	25.6
Glue	40.0	40.0	0.0	80.0

[a] The GER values are broken down into feedstock energy that is embodied in the final product and both electricity and primary energy that is used in various production and transportation processes in the production of the final product. Recycled materials have zero feedstock energy by definition. To be able to add the $GJ_{primary}$ and $GJ_{electricity}$ we have assumed an efficiency of 40% to convert primary energy into electricity.

3.1. Data on energy use and CO_2 emissions

For all reference and improved packages the life cycle is described in terms of energy consumption. We discern energy consumption for material production, packaging making, filling, transport, maintenance, waste collection and waste management.

To calculate the energy consumption for material production we use the gross energy requirements (GER) for the materials involved. The GER value of products is equal to the embodied energy (feedstock) plus the amount of energy that is used for the production and transportation of feedstocks, semi-finished products and the final product. In Table 1, these GER values are stated for the materials used in this study.

The energy use for manufacturing depends on the type of package and the production processes involved, e.g. injection moulding for pallet and crate production, extrusion of plastics film for production of shrink covers and stretch films, and production of boxes from corrugated board. In Ref. [9] the energy requirements of these processes are presented in MJ_{el}/kg package. The results are summarized in Table 2. From this table one can see that the energy requirements for packaging making are sometimes negligible compared to the energy requirements of the production of the materials involved [9].

After producing the package, it also needs to be filled. For the investigated improvement measures, the energy requirements for filling transport packaging does not differ significantly. Therefore, data for filling transport packages are not part of the calculations. However, there is one exception, which is the use of shrink covers. For this type of packaging extra energy is needed for heating the cover to make it shrink. The energy requirements for this process are taken into account.

The energy that is necessary for transportation of the packed products to the stores is allocated to primary packaging [8]. To avoid double counting, in this study we do not take these energy requirements into account. However, we do take the extra transport into account that is necessary when multiple use transport packaging is used. In many cases, multiple use transport packaging is part of so-called 'packaging pools'. A packaging pool refers to a service organization that owns returnable pallets and crates. These pallets and crates are rented by the distributors. The advantage of such a pool system is that the individual distributors need to keep less pallets and crates in storage for sudden demand fluctuations. We will model a system where crates and pallets are returned to the pool owner after each product delivery for cleaning. We will assume average transport distances of 100 km between pool owner and distributor and between pool owner and customer[2].

Cleaning of transport packaging is only needed for multiple trip packaging. We will use average energy requirements for large cleaning facilities [12].

Packaging waste is either landfilled or incinerated. Incineration plants can produce heat and electricity. In Western Europe 75% of the final packaging waste[3] is landfilled and 25% is incinerated [13]. Thirteen percent of the waste is incinerated with energy recovery, either heat (54%), power (12%) or combined heat and power (34%) [13,14]. For plants that just produce electricity we assume an efficiency of 24%, for plants that produce heat we assume an efficiency of 80% and for the CHP

Table 2
General energy use data for several packaging processes and packages[a] [9,11,13]

	Packaging (MJ_{el}/kg pack)	Filling making (MJ_{el}/kg pack)	Cleaning (MJ_{el}/1000 pack)	Transport (MJ_{prim}/1000 trips)
Plastic crate	3.1		270	4590
Stretch film	2.6			
Corrugated box	0.1			
Shrink cover	2.6	7.56		
Paper bag	neg.			
PP bag	2.6			
Wooden pallet	neg.			
Plastic pallet	3.1		270	5048

[a] The abbreviation neg. is used to indicate that the energy use for packaging making is negligible to the energy use for materials production. Empty cells indicate that the energy use for filling is the same for all packaging concepts, for shrink covers extra energy is needed. The empty cells for cleaning and transport indicate that no energy is required for the packaging concepts.

[2] This is based on the fact that a large Dutch pool owner has two central facilities in The Netherlands [41].

[3] Final waste is waste that is left after recycling.

Table 3
CO_2 emission factors for electricity, primary energy carriers and packaging materials as used in this study [16,17]

	Electricity	Coal	Oil	Gas	Wood	PC	PE	PP	Corrugated board
kg CO_2/GJ	123.6	94.6	73.3	63.1	0.0				
kg CO_2/kg					0.0	2.8	2.8	2.8	0.0

Table 4
Material costs for several packaging materials [11,20–22]

Material	Market-price (ECU/kg)
LDPE (film) [20]	1.14
HDPE (film) [20]	1.23
HDPE (injection moulded) [21]	1.01
Recycled PE (film) [21]	0.60
Recycled PE (injection moulded) [21]	0.49
PP [20]	0.70
Paper [22]	0.47
Corrugated board [22]	0.30
Wood [11]	0.25
Recycled PC [21]	2.09

installations we assume an electrical efficiency of 17% and a thermal efficiency of 60% [15].

When the energy use of the packaging life cycle is calculated and specified for the different energy carriers used, the CO_2 emissions for that life cycle can be calculated. For emissions from electricity production and primary energy use we use average CO_2 emission data for Western Europe [16,17]. CO_2 emission factors for incineration of plastics are derived from the oxidation reactions. For paper, board and wood packaging we assume that no net CO_2 emissions are emitted due to the renewable nature of the feedstock. In Table 3, the CO_2 emission factors for the different energy carriers are stated.

3.2. Data on costs

The life-cycle costs of reference and improved packages are calculated by summation of the costs for material production, packaging manufacture, transport, recycling, and waste management.

We use market prices of the packaging materials as an estimate for the material production costs. These costs are stated in Table 4. All costs are expressed in 1995 ECU (European Currency Unit), which equals approximately 1.3 US$ (1995) and 2.1 Dfl (1995) [18].

The costs of packaging manufacture depend on the investments for the packaging line and the costs of operation. No detailed data on investment and operation costs are available for the different packaging concepts. We therefore calculate the production costs by subtracting the material costs from the average prices of the packaging concepts and taking a 10% profit margin into account [19]. The data on prices, material costs and production costs per 1000 packages are stated in Table 5. In Table 6 the production costs are also stated per 1000 packaging trips.

The costs for filling the transport package do not differ significantly between different transport packages and are therefore not included in the calculations.

The costs for extra transport of the returnable packages as stated in Table 6 are estimated by assuming an average transport distance of 100 km and a total delivery time of 3 h. Furthermore we assume that 1 h is needed for loading or unloading a truck. A total cost (truck + labor) of ECU 22 per h is assumed [12]. For returnable transport packaging, extra costs for storage at the premises of the retailer are taken into account. These costs are based on the assumptions that floor surface costs ECU 162/m^2 per year [12] and that empty pallets and crates are stored for 1 week before they are returned to the producer.

When returnable packages are used, extra costs have to be made for organizing a system where pallets and crates are returned after usage (see Section 5.5). In Table

Table 5
Prices, material costs and production costs of transport packages [19,23–28]

	Prices (ECU/1000 pack)	Material costs[a] (ECU/1000 pack)	Production costs (ECU/1000 pack)
Multiple use PE pallet [23]	75 000	30 400	40 100
Multiple use recycled PE pallet [23]	25 000	14 600	9400
Multiple use recycled PC pallet [23]	75 000	30 800	39 900
Single use wooden pallet [23]	5000	4300	680
Multiple use wooden pallet [23]	20 000	6300	12 400
Corrugated pallet [24]	6000	1800	3800
Pressed wood pallet [24]	5000	4000	900
Plastic crate [25]	3000	2000	875
Wooden crate [26]	1000	550	400
Corrugated box [27]	700	250	400
Pallet covers [27]	2100	1500	550
Pallet shrink film [27]	850	600	250
Grouping film [27]	40	25	10
Carrier bag [19]	70	25	40
Paper bag [19]	110	25	75
Reusable bag [19]	509	170	300
Industrial bag [19]	360	120	220
Industrial paper bag [19]	390	130	240
FIBC [28]	3700	1200	2200
Returnable FIBC [28]	6360	2100	3800

[a] Calculated by combining the packaging characteristics as described in Section 5 with Table 4.

Table 6
Costs of packaging making, transport, organization, storage and cleaning [12,19,23–29][a]

	Production (ECU/1000 trips)	Transport (ECU/1000 trips)	Organization (ECU/1000 trips)	Storage (ECU/1000 trips)	Cleaning (ECU/1000 trips)
Multiple use PE pallet	535	675	500	49	3
Multiple use recycled PE pallet	130	675	500	49	3
Multiple use recycled PC pallet	530	675	500	49	3
Single use wooden pallet	680				
Returnable wooden pallet	300	675	500	49	3
Corrugated board pallet	3800				
Pressed wood pallet	200	340	500	49	3
Plastic crate	10	370	150	22	3
Wooden crate	80	370	150	22	3
Corrugated box	400				
Pallet cover	550				
Pallet shrink film	250				
Grouping film	10				
Carrier bag	40				
Paper bag	75				
Reusable bag	300				
Industrial bag	220				
Industrial paper bag	240				
FIBC	2200				
Returnable FIBC	750				

[a] Empty cells indicate that no transport, pool organization, storage or cleaning are necessary for these packaging concepts.

6 these 'pool costs' are based on the tariffs that are used by pool organizations in The Netherlands [29]. Returnable packages are often cleaned before they are used again. The costs as stated in Table 6 are based on the use of large cleaning facilities [29].

Waste management costs are differentiated between costs for landfilling (95.3 ECU/t) and costs for incineration (156.3 ECU/t) [30].

The costs of recycling are only taken into account when the recycled material is used for packaging purposes. This is done by using market prices of recycled material.

4. Material use for transport packaging in Europe

To estimate the potential of material efficiency improvement for transport packaging information is needed about the current material input[4]. The plastic demand for production of carrier bags is estimated at 430 kt [13,31]. Carrier bags are most often made out of PE. The amount of plastic (PE) industrial bags is estimated at 460 kt [31]. Industrial bags can also be made out of paper. The amount is estimated based on the cement production in Europe because these bags are used mainly for cement packaging. Ten percent of the European cement production is packed in bags [32]. The amount of paper is estimated at 85 kt and due to the PE layer in these bags the PE demand is estimated at 15 kt [32]. Transport boxes can either be made out of corrugated board (11 700 kt) or PE (884 kt) [13,22]. The amount of grouping films amounts to 290 kt in 1990 [31]. We estimate the 1995 demand at 310 kt based on the average growth of PE consumption in Europe [13,31].

The demand for pallets in Europe is 280 million per year [33]. The majority of these pallets is made from wood (96%). Taking into account that a single use pallet weighs 17 kg and a multiple use 25 kg and that 66% of the pallets are single use, the total wood use is calculated at 4956 kt [33,34]. The remainder of the pallets is assumed to be made from PE which adds 336 kt to the material use when an average weight of 30 kg is assumed [35]. Transport films can be subdivided in shrink covers (380 kt of PE) and stretch film (320 kt of PE) [31][5]. An overview of the total material use per category is stated in Fig. 2. The figure suggests that the plastics demand is totally satisfied by PE. This is not the actual situation. Division of total European packaging films by resin shows that 81% of the resins used is PE, 14% is PP, and 4% are others [13]. In Fig. 2 no differentiation is made between PE and PP because no information is available on the PP shares for the various categories.

[4] No information was found on efficiency improvements for steel barrels. In the material use analysis, steel consumption for steel barrels is therefore not taken into account.

[5] 1990 data from Ref. [28] extrapolated to 1994 with growth rate of PE consumption.

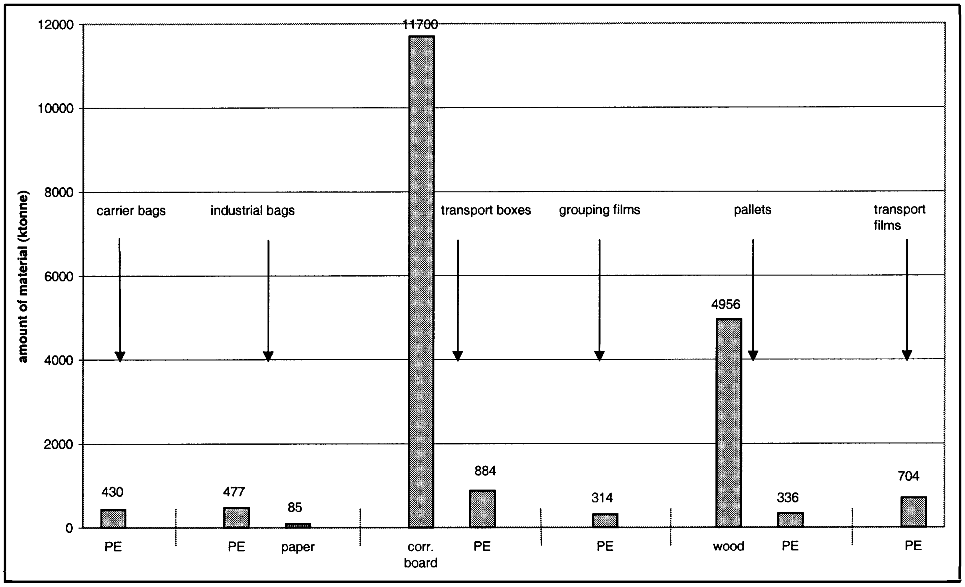

Fig. 2. Material demand for transport packaging in Europe in 1994.

Fig. 2 shows that the corrugated board is used most for transport packaging (11.7 Mt), followed by wood (about 5 Mt) and plastics (about 3.5 Mt). Only a small amount of paper is used (about 0.1 Mt).

5. Reference and improved packaging concepts

In this section, we describe both the reference and the improved packages. Reference packages are model packages that have characteristics that correspond to the average characteristics of types of transport packaging in Europe. We will describe the packages by packaging category and by material type used.

5.1. Carrier bags

Carrier bags are most often made out of plastics, more specifically, most bags are made from LDPE [36]. The thickness of the films used for the production of carrier bags varies between 10 and 200 μm. The average carrier bag in The Netherlands weighs 20 g and has dimensions of 40 × 35 cm [37]. Based on this we have defined a reference carrier bag that is made out of LDPE, weighs 20 g, has dimensions of 40 × 35 cm, and a thickness of 66 μm.

Several measures can be applied to reduce the material demand and related CO_2 emissions for carrier bags. The first measure is to reduce the weight of the carrier bags. Substitution of LDPE by HDPE reduces the weight of carrier bags by 20%

[38]. Co-extrusion of plastic films also leads to weight savings of 20%[6] [37]. We will model these developments by defining a light bag that weighs 20% less.

Another possible measure to reduce material related CO_2 emissions is substitution of the material types used. PE can be substituted by paper. Paper bags are heavier than the average plastic bag. An average paper bag with the same dimensions as the PE bag weighs 56 g [37]. We assume that full penetration of this option is technically possible.

Most carrier bags are made from virgin PE. Besides virgin PE, recycled PE can also be used. The recycled PE content can be 15–20% without changes in the appearance and strength of the bag [19]. If carrier bags are made from 100% recycled resin the weight increases by 50% [19]. We model a bag made from 100% recycled resin that weighs 30 g as an improved package. We assume that full penetration is technically possible.

The last option is to reduce the amount of bags. In The Netherlands, the government and retailers agreed that plastic bags should not be handed out for free [38]. This resulted in a reduction of the amount of carrier bags because consumers started to reuse bags or make use of durable carrier bags. We will model this option by defining a bag that can be re-used. The model re-usable bag is made from PP straps, weighs 240 g and has a lifetime of 100 shopping trips [39]. Technically, full penetration seems to be possible. However, this will require large behavioral changes of the European consumers.

5.2. Industrial bags

Industrial bags are used to pack products like plastic granulate, animal feed, fertilizers, soda, and cement. A large variety in size and thickness is used. We define a reference plastic industrial bag that is capable of carrying 25 kg which is an often used size due to the handling characteristics of 25-kg bags [32] The bags, made from HDPE, have a thickness of 150 μm and weigh 105 g [40,41]. Besides plastic bags paper bags are also used to pack products like cement and fertilizer. The bags are often multi-wall paper with a PE moisture-proofing layer. We have defined a reference paper bag that weighs 262 g (252 g paper and 10 g LDPE) and has the same size as the plastic industrial bag [41].

Unlike carrier bags we do not expect that much savings on the bag weight is possible because strength characteristics are very important for industrial bags and reduced performance of industrial bags leads to large costs due to product loss.

The only improvement option that we will model is the substitution of PE bags by the Flexible Intermediate Bulk Container (FIBC). The FIBC is made from woven PP straps (200 g/m^2) and weighs around 1.5–2 kg. The carrying capacity is 1000 kg. In principle this bag is only used once. Multiple use bags are also delivered

[6] Tables 1 and 2 show that the energy use for packaging making is small compared to the energy use for plastics production. We have therefore assumed that an increase in energy use for co-extrusion compared to normal extrusion is negligible for the total energy use related to the production of carrier bags.

even though they are not used very often. These bags are made from heavier material (240 g/m^2) and have reinforced carrying straps [28]. We assumed that implementation of this option is only technically possible when it is used for professional purposes. We estimate that the majority of industrial bags are used for industrial purposes (90%).

5.3. Transport boxes

The most common transport boxes are the boxes made from corrugated board. These boxes are suitable to transport dry food and non-food products. In fresh-products sectors, e.g. fruit and meat sector, the most common transport box is the crate. A crate is an open transport box (no top or lid) with generally a larger floor surface and a smaller height. In the fruit sector crates from corrugated board are common while in the meat sector plastic crates are standard.

5.3.1. Corrugated box

We define the reference corrugated box as having a volume of 40 l ($40 \times 60 \times 17$ cm) and a weight of 800 g [27]. Boxes of 40 l are often used for transport of food products and for this size of box, 800 g is an average weight [27].

Several options are available to improve the standard corrugated box. New box making machines have been introduced to the market that for example make better use of corrugated board due to improved gluing techniques (less overlap of corrugated board is needed). Savings of 15% corrugated board have been reported [42]. Shape-renewal of boxes has also led to the use of less corrugated board, e.g. in some cases it is possible to remove the top flaps of the boxes which leads to savings of 20–30% [42,43]. In other cases, it was possible to reduce the box height [43,44]. Also projects demonstrated the potential of improving the packaging operation itself. Standardization of primary packages, for example, saved 20% corrugated board by a milk producer since only one type of box was required that is smaller than the average size of the boxes used before [42,43]. Also more efficient stacking of primary packages and changing the primary packaging design resulted in smaller transport box sizes [42–44]. Concentration of the product or a smaller primary package can lead to major savings in transport packaging. Savings of 16–30% have been reported in the period 1992–1996 by the use of smaller primary packaging and concentration [36,42,43]. Based on all these experiments where savings in the range of 15–30% are reported we assume that 20% less corrugated board is needed to fulfil the same packaging need. We model this as a lightweight box that weighs 20% less.

5.3.2. Crates

Crates are normally used to pack loose products like fruit and vegetables, meat and product parts[7]. The crates can be used for one-way shipping or function as a

[7] Crates are also used for transportation of bottles. No improvements for these crates have been modeled.

returnable package. The one-way crate is mostly made out of wood or corrugated board and is normally used to pack fruit and vegetables. No information is available on the market shares of wooden and corrugated crates. Corrugated crates have better printability properties and need less storage after being used since they can be pressed together. Therefore, we will model the corrugated crate as the reference 'single use' crate. The standard corrugated board 'single use' crate weighs 600 g and has a volume of 40 l[8] [27].

Instead of one-way crates, multiple trip plastic crates can be used. These crates can compete with both the corrugated crate and the corrugated box. The plastic multiple use crate is made from HDPE, weighs 2 kg and has a volume of 40 l [44]. Using plastic returnable crates requires a closed loop transport system. A third party often manages the logistics of this transport system. The crates currently used have a lifetime of 5–10 years and the average trippage rate is 25/year [25,45]. We will model a trip number of 150 trips per life cycle.

5.4. Grouping films

We defined 'grouping films' as all plastic films that are used to group or bundle multiple packed products. As such they compete with corrugated boxes. To group multiple primary packages mostly shrink film is used. In many cases the primary packages are placed on a tray from corrugated board, and shrink film is winded loosely around the packages. The film is subsequently heated in order to shrink and thereby bundling the packages. Shrink films are generally made out of LDPE and have an average thickness of 30–80 μm before shrinking. The most used thickness is 50 μm [40]. In this study shrink films are compared to corrugated boxes and therefore the standard dimensions of these industrial packages are chosen as the standard dimensions for shrink films ($40 \times 60 \times 17$ cm, 40 l). For packing this volume, 200×25 cm LDPE is needed (23 g) and 150 g corrugated board.

Several projects in the period 1992–1994 show that shrink films are often over-designed. The thickness of shrink films for packing cans was reduced from 60 to 45 μm and the thickness of films to pack cardboard boxes was reduced from 50 to 40 μm [34,40]. Based on these projects we assume that a reduction of 10% is technically feasible before the year 2010.

Replacement of corrugated boxes by grouping films is only possible when the primary package is rigid and offers enough protection to the contents when transported without a corrugated box. This is the case for about 20% of the primary packages currently transported in boxes [39].

5.5. Pallets

The vast majority of the pallets used in Europe are made out of wood. Wooden pallets are popular because they are cheap, have a large carrying capacity, and are

[8] When modeled, crates and corrugated boxes only differ in weight. In reality their appearance is quite different and they are used for different purposes.

easy to repair when broken. Moreover, they are very suitable for production of small series with deviating sizes. About one-third of the pallets are returnable [33]. We will therefore define two reference pallets: a single use wooden pallet and a multiple use wooden pallet. A single use pallet weighs about 17 kg and a multiple use pallet weighs about 25 kg [34]. On average returnable wooden pallets make 20 trips [33]. The most used wood types are spruce, pine and poplar. Three pallet types are on the market that may be an improvement for the wooden pallet: plastic pallets, corrugated fiberboard pallets and pressed wood fiber pallets.

5.5.1. Plastic pallets

Plastic pallets are used a lot in the food industry because they are easy to clean due to the smooth surface. Furthermore, no liquid can be absorbed by the pallets [46]. The most common material for plastic pallet production is PE but in some cases, recycled PC is also used. Pallets made out of PC are stronger than PE pallets. Plastic pallets are especially suitable as multiple use pallets. They weigh around 30 kg [23,35]. There is no consensus about the number of trips that can be made with a multiple trip plastic pallet. In ref. [35] the trip number is estimated at 34, while in Ref. [24] a lifetime of 100 trips is assumed. In several other publications it is stated that a plastic pallet is much more durable than wooden pallets [23,33]. We will therefore use a trip number of 50.

The shift from one-way pallets to returnable pallets requires a large shift in pallet administration and management. The use of multiple trip pallets requires a pallet pool. A pallet pool is an organization that manages the transit of the pallets between the various users. As a result of pallet pools, standard sizes for pallets are introduced to make the pallet applicable for many users. In Europe several organizations are active in the management of pallet pools of which Europool and Chep have the largest market shares [47].

5.5.2. Corrugated fiberboard pallets

Pallets made from corrugated fiberboard are an option to replace single trip wooden pallets. Some types are made from solid corrugated board and are capable of making more than one trip but most pallets made from corrugated board will be used for single trips. The pallet is cheap compared to wooden and plastic pallets and weighs about 6 kg which makes it a very lightweight pallet [24]. This has already been a reason for some companies to use this pallet since it reduces the weight in the trailer [48]. A large disadvantage of these pallets is that they are not resistant to water.

5.5.3. Pressed wood fiber pallets

Pallets can also be made from pressed wood fibers. The advantage of these pallets is that they can save a lot of space if they are used for multiple-trip purposes because they use a quarter of the space of piled wooden pallets when stacked empty. Pressed wood fiber pallets are made from low-grade fibers, mostly from bark and thinnings. The fibers are molded into a pressed wood pallet with the use of synthetic organic resins (glue). The average weight of the pallet is 16 kg [24].

Pressed wood fiber pallets are designed for one trip but are often used more often [24,33]. We use a trip number of five trips per pallet [24].

5.6. Transport films

Transport films are used to bundle secondary packages, e.g. corrugated boxes, on a pallet. Two kinds of transport packaging are used: shrink covers and stretch films. Shrink covers are wound loosely around the boxes and are subsequently heated in order to shrink and form a tight bundle. Stretch films are wound tightly around the boxes. Thereby they are stretched for about 30% and are normally wrapped ca. three times around the load to be bundled [40]. Stretching is less energy consuming than shrinking. Furthermore, stretching can be mechanized more easily. Shrink and stretch films are generally made of LDPE. HDPE has poor shrinking and stretching properties and is therefore not usable as a transport film.

In 1990 the average shrink cover in The Netherlands had a thickness of about 200 μm [49]. Since then, partly because of the Packaging Covenant[9], it has dropped to an average of 100 μm [49]. Because in The Netherlands more actions have been taken to reduce the amount of packaging waste compared to the European average we expect that the average shrink cover in Europe weighs more than the Dutch average. We therefore assume that the average shrink cover in Europe has a thickness of 125 μm. To cover a standard pallet ($1.2 \times 1.0 \times 1.6$ m) a shrink cover of $1.25 \times 1.05 \times 2.20$ m is needed [19]. This results in a weight of 1.31 kg for a reference shrink cover[10]. Improvement of the shrink film is possible by reducing the thickness to 100 μm, resulting in a weight of 1.04 kg [50].

Stretch films have an average thickness of 25–40 μm [40]. We assume a mean thickness of 35 μm for the standard stretch film. The weight of the stretch film needed to pack one standard pallet is calculated at 513 g, assuming that 32 m of foil with a width of 0.5 m is needed [19]. Improved stretch film is 20% lighter [50].

In Table 7 the above is summarized by stating the life-cycle costs, material consumption and CO_2 emissions for all reference and improved packages. The values are expressed per functional unit.

6. Potential for CO_2 emission reduction

In this section, we assess the consequences of implementing the selected improvement options. By implementing the improved packages, savings in CO_2 emission can be achieved.

In the reference system, the total CO_2 emissions related to transport packaging in Europe are calculated at 29 Mt per year. This figure is calculated by combining the material requirement and CO_2 emission of reference packages as stated in Table 7

[9] The Packaging Covenant is an agreement between the Dutch government and the Dutch packaging industry to reduce the amount of packaging waste.

[10] Based on a surface of 11.4 m^2, a thickness of 125 μm, and a density of PE of 930 kg/m^3.

Table 7
Measures for reducing CO_2 emissions related to transport packaging expressed per functional unit[a]

Packaging category	Packaging concept	Total CO_2 emission (kg/f.u.)	Total costs (ECU/f.u.)	Total material (kg/f.u.)
Carrier bags	LDPE	101	73	20
	Light *HDPE*	81	68	16
	Recycled *LDPE*	6	68	30
	Paper	42	116	56
	Reusable bag	11	5	2
Industrial bags	HDPE	213	153	42
	Paper	49	113	52
	FIBC	83	39	18
	FIBC returnable	29	14	6
Transport boxes	Corrugated box	729	776	800
	Light corrugated box	583	717	640
	Corrugated crate	547	703	600
	Wooden crate	190	240	440
	Plastic crate	472	668	20
Grouping films	LDPE	253	87	173
	Light *LDPE*	227	80	156
Pallets	Wood, one-way	7255	6527	17 000
	Wood returnable	670	1782	625
	HDPE returnable	2441	2292	400
	Recycled *HDPE* return	493	1604	400
	Recycled *PC* return	493	2293	400
	Corrugated one-way	5439	6569	6000
	Pressed wood mult.	2412	2513	3200
Transport films	Shrink cover	6615	2333	1305
	Light cover	5292	2019	1044
	Stretch film	2595	942	512
	Light stretch film	2078	819	410
	No stretch film	284	467	50

[a] New packaging concepts and concepts currently with a small market share are shown in italics. In this table all described reference and improved packages are listed. The possible substitutions for CO_2 emission reduction are listed in Table 8.

Table 8
Potential savings and costs of packaging efficiency improvement measures in Europe for the reference year 1994[a]

No.	New packaging concept	Old packaging concept	Degree of substitution (%)	CO_2 emission reduction (%)	Costs (ECU/t CO_2)
S1	Light corrugated box	Corrugated box	100	−6.9	−400
S2	Light LDPE grouping film	LDPE grouping film	100	−1.2	−288
S3	Light shrink cover	Shrink cover	100	−1.3	−238
S4	Light stretch film	Stretch film	100	−1.1	−238
S5	Light HDPE carrier bag	LDPE carrier bag	100	−1.5	−238
M1	LDPE grouping film	Corrugated box	20	−4.8	−160
M2	No stretch film	Stretch film	100	−1.9	−32
M3	One-way corrugated pallet	One-way wooden pallet	100	−1.1	−3
M4	Recycled LDPE carrier bag	LDPE carrier bag	100	−5.5	0
M5	Recycled HDPE returnable pallet	Returnable wooden pallet	100	−0.6	31
M6	Paper carrier bag	HDPE carrier bag	100	−2.9	67
L1	Reusable carrier bag	Recycled LDPE carrier bag	100	−4.9	−440
L2	Reusable carrier bag	Paper bag	100	−2.8	−270
L3	Recycled HDPE returnable pallet	One-way corrugated pallet	100	−3.0	−89
L4	FIBC	HDPE industrial bag	90	−5.2	−79
L5	Recycled HDPE returnable pallet	One-way wooden pallet	100	−4.2	−66
L6	FIBC returnable	FIBC	100	−2.1	−43
L7	Plastic crate	Corrugated box/crate	50	−12.3	16

[a] A division is made between the options with small complexity of implementation (S1–S5), the measures with medium complexity of implementation (M1–M6) and the measures with a large complexity of implementation (L1–L7).

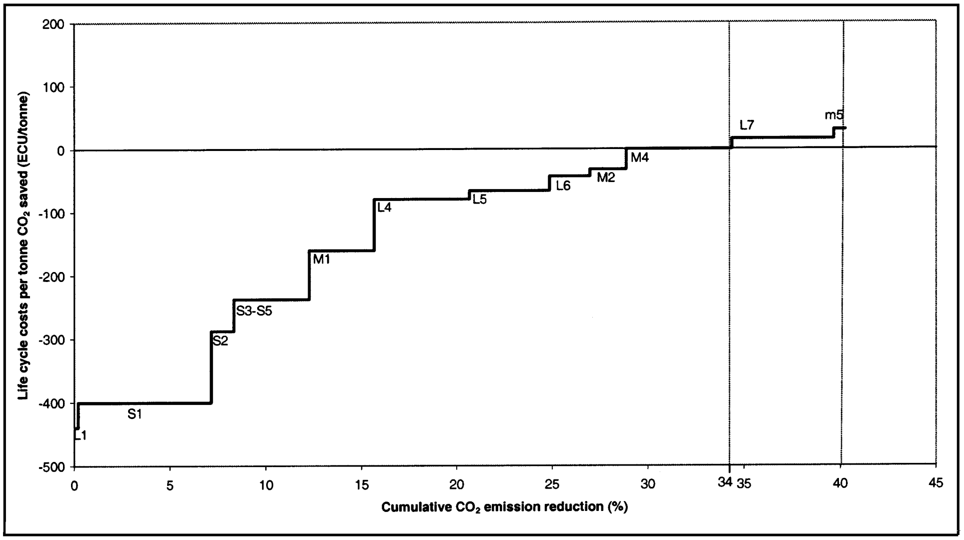

Fig. 3. Supply curve of CO_2 reduction measures for the manufacturing and use of transport packaging. The horizontal axis depicts the cumulative reduction in CO_2 emission (in %) that can be achieved. The vertical axis depicts the life cycle costs per tonne abated CO_2 emissions. The numbers refer to Table 8.

with the total material requirement for transport packaging as stated in Fig. 2. The CO_2 emissions related to transport packaging correspond to 1% of Western European anthropogenic CO_2 emissions in 1990 due to fossil fuel combustion; calculated from UN-FCCC emission data [52].

Table 8 shows the CO_2 emission reduction potential of the individual improvement measures (replacing reference packages by improved packages) and the costs of these options measured in ECU per tonne CO_2 saved. The total reduction potential identified in Table 8 adds up to 63%. The CO_2 emission reduction figures in Table 8 represent savings that are possible when packaging technology that is available in 2010 would already have been implemented in 1990.

In Table 8 the anticipated change in the packaging system is indicated by a division of the possible measures into three categories. The table discerns measures with small complexity of implementation (S1–S5), measures with medium complexity of implementation (M1–M6) and measures with a large complexity of implementation (L1–L7). The measures with small complexity of implementation correspond to the use of less, lighter and thinner materials. Only changes at the level of the packaging manufacturer are necessary. Measures with medium implementation difficulty involve measures where material substitution takes place. Material substitution leads to changes in the material production sector and the packaging-manufacturing sector. Measures with a large complexity of implementation involve returnable packages where changes in all stages of the packaging life cycle are necessary. Also measures that rely on a change in consumer behavior are part of this category.

Figs. 3 and 4 depict the cumulative savings of all measures by means of a supply curve. Contrary to Table 8, the potential reduction of CO_2 emissions for each improvement measure is corrected for inter-measure influences.

In Fig. 3 all measures are depicted in order of cost-effectiveness. The numbers of the measures correspond to the numbers in Table 8. The supply curve obtained shows that the total cumulative CO_2 emission reduction that can be achieved amounts to 40%. The absolute savings in CO_2 emission can therefore be calculated at 12 Mt per year. This is 0.4% of Western European anthropogenic CO_2 emissions in 1990 due to fossil fuel combustion. The main part of this potential (33%) is calculated to be cost-effective based on a life cycle approach.

Fig. 3 does not give any information about the potential of the measures in relation to the degree of implementation difficulty. In Fig. 4 this relation becomes clear. Here, we assumed that measures are implemented in order of implementation difficulty where the least complex measures are implemented first. In Section 3 we already described that in this paper we link the difficulty of implementation to the anticipated change in the entire packaging system. The potential savings on CO_2 emissions of measures with low implementation complexity is 12% and measures that are more difficult to implement can add another 12%. The potential for emission reduction is increased by another 16% by implementing measures with a large complexity of implementation.

The order of implementation influences the potential of the individual measures due to inter-measure influences. Therefore the improvement potential that is depicted in the supply curves (40%) is smaller than the addition of the individual savings as stated in Table 8 (60%). This effect is visible in two ways.

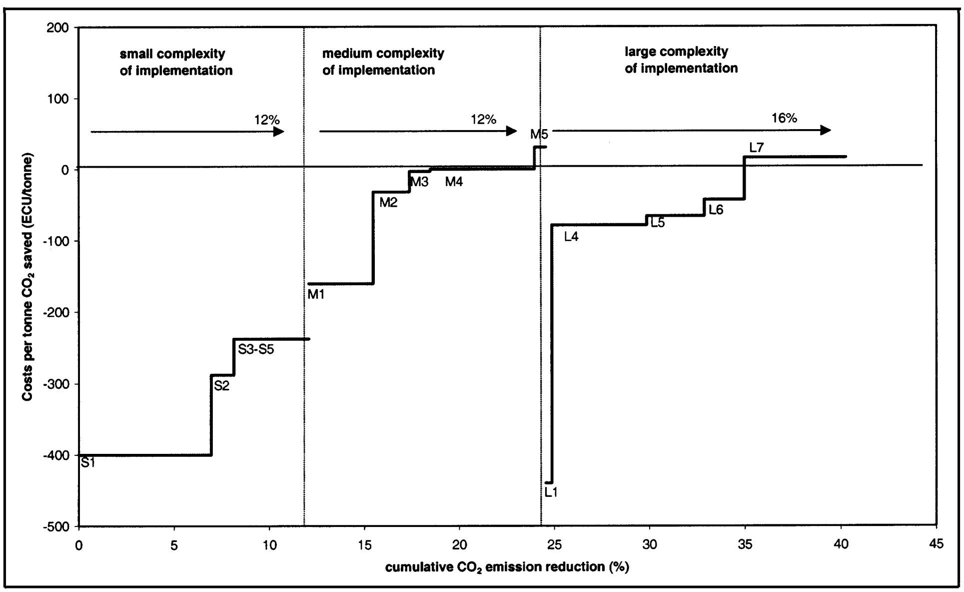

Fig. 4. Supply curve of CO_2 reduction measures for the manufacturing and use of transport packaging. The different sections refer to different levels of complexity of implementation.

First not all measures listed in Table 8 are part of the supply curves because the order of implementation prevents them from being implemented. Fig. 3 shows that measures M3 and M6 are not implemented since all wooden pallets are replaced earlier by returnable plastic pallets and LDPE carrier bags are replaced earlier by reusable carrier bags. In Fig. 4 measures M6 and L5 are not part of the improvement potential. In this case the paper bag is not introduced due to an earlier introduction of the recycled PE bag. The wooden pallet is not replaced by returnable PE pallet since the wooden pallet is replaced earlier by the corrugated pallet.

Second, the potential of some measures in the supply curves are smaller than the potential in Table 8 because in the supply curves the potential is calculated in relation to earlier implemented measures. An example of this effect is measure M4 where the LDPE carrier bag is substituted by the recycled LDPE carrier bag. In the supply curves measure L5 is taken first which corresponds to implementation of a light LDPE bag. Therefore the potential of measure M4 is smaller in the supply curves than in Table 8.

7. Discussion

In this study we have calculated for all transport packaging in a large geographical area (Western Europe) the CO_2 emission reduction that can be achieved by more efficient management of materials. To do so, it is inevitable to make assumptions regarding production, use and waste management of transport packaging in Europe. In this section we will discuss the reliability of the data used and assumptions made in this study.

Of the energy data used in this study, the energy requirements for material production proved to be the largest contributors to the total energy requirement for single use packaging. We used GER values from a Swiss study as an estimate for these energy requirements. These values are based on a number of European sources [9]. We therefore expect that these GER values are representative for the average European situation.

For returnable packaging, energy requirements for transport are also important for the total result. The most important assumption for the calculation of the energy requirement of transport is that extra transport activity of 200 km is necessary for returnable transport packaging. The results of the calculations are very sensitive for this assumption. Replacement of the corrugated box by returnable plastic crates adds currently about 5% to the total reduction potential. When the transportation distance is 50% less, then the use of plastic crates adds 14% to the total reduction potential, thereby adding 9% to the total CO_2 emission reduction. This is the result of the large influence of corrugated boxes in the total material use of transport packaging (Fig. 2). However, when the transportation distance is doubled, the plastic crate is no longer an improvement option. Depending on the density of population, the average transportation distance will differ between European regions. However, in many cases no extra transport will take place for returnable transport packaging because the crates and pallets are not returned to the pool owner but directly to the distributor. In that case the same truck that is used for the transport of the packed products is also used to return the packaging. Based on this we expect the extra transport of 200 km to represent the upper limit. Therefore, for this option the results should be viewed as an estimate of the lower limit of the technical CO_2 emission reduction potential.

Energy efficiency improvements in material production processes are not taken into account. Improvements in energy efficiency will lower the potential for CO_2 emission reduction due to more efficient material management.

For the costs calculations of single use packaging the most important parameters are costs for material and packaging production. We estimated the packaging production costs by subtracting material prices from packaging prices. Material market prices vary strongly over time. For PE the price increased from $830 to $1190/t in the period 1996–1997; an increase of 43% [20]. Paper prices are notorious for their cyclical nature. The price of containerboard, for example, rose in the period 1993–1995 from $300 to $580/t and fell back to $250/t in the period 1995–1996 [51]. Also the prices of packaging products are likely to change over time and are likely to be sensitive for the geographical region where it is produced. Price fluctuations have large effects on the calculated costs per tonne CO_2 saved. For example, a decrease in corrugated board costs by 50% results in an increase in costs of measure L7 from + 15 ECU to + 100 ECU/t CO_2 saved. Based on this the cost efficiency of the measures should be interpreted with care.

For returnable packaging, costs for transport and administration are also a substantial part of the total costs. Because we assumed in the calculations that all packages are returned to the pool owner after being used these costs are likely to represent the upper limit. When for example packages are returned to the pool owner after being used twice the costs of measure L7 decrease to − 50 ECU/t CO_2 saved.

To model current and improved packaging practices in Western Europe we defined reference and improved packages. The definitions of the reference packages do not influence the reduction potential of the measures in the first category (low complexity of implementation) because all improvements are stated as relative changes. However, the measures in the second and third category are strongly influenced by the definition of the reference packages because the savings in CO_2 emissions are related to the difference between two reference packages. When reference corrugated boxes for example are modeled to be 10% lighter the CO_2 emission reduction potential of substituting corrugated boxes by shrink foils would decrease from 5.3 to 2.5%. We expect this effect to be strongest for measures related to corrugated boxes because this packaging category is very diverse in shape and weight. A reference corrugated box is therefore more difficult to determine than reference packages in other more homogenous categories.

The potential of measure S1 (light corrugated box) is uncertain. We estimated a possible reduction in corrugated board use of 20% to be possible. This reduction is based on many different measures that can be taken in the field of corrugated board packaging. These measures are individually proven but the total potential of the sum of these measures for all corrugated packaging in Europe is difficult to determine. The reductions realized by the individual measures range from 15 to 30%. This range leads to a range in CO_2 emission reduction potential of measure L1 of 5.2–10.4%.

The potential reduction in CO_2 emission for returnable packaging is strongly dependent on the assumed trip number. In this study we assumed a trip number for plastic crates of 100 trips. A reduction of this trip number by a factor of two would diminish the reduction potential of this measure from 5.3% to zero. When the trip number is doubled, the potential increases by a factor of 1.5–7.7%.

To improve the reliability of the results, more detailed data on the use of packaging are necessary. Also more insight in the differences in packaging culture and tradition for all European countries would certainly improve the results. More regional or national studies on packaging are necessary in order to increase detailed data availability.

We used the term complexity to take implementation difficulties into account. Fig. 4 shows that measures with a large complexity of implementation have the highest potential to reduce CO_2 emissions. If the measures with small and medium complexity of implementation were not implemented first the potential would be even greater[11]. The large complexity of implementation suggests that for successful implementation high transaction costs need to be made. However, these high transaction costs make it possible for specialized companies to enter new markets. For transport packaging, the pool organizations are good examples. The presence of these specialized companies drastically lower the transaction costs of measures with a large complexity.

8. Conclusion

Several materials are used for transport packaging. Corrugated board is used most (11.7 Mt), followed by wood (about 5 Mt) and plastics (about 3.5 Mt). Only a small amount of paper is used (about 0.1 Mt).

The total CO_2 emissions related to transport packaging in Europe is calculated at 29 Mt per year. This corresponds to 1% of Western European anthropogenic CO_2 emissions in 1990 due to fossil fuel combustion.

We have studied the potential of a large number of technical measures that can be applied till the year 2010 to improve material management of transport packaging. Also we estimated the potential impact on CO_2 emissions in Western Europe when the packaging demand in 1995 would be fulfilled with these improved packages. This resulted in five measures that improve current packaging by using less or lighter materials. Full implementation of these measures might result in a reduction of the CO_2 emissions related to the production and consumption of primary packaging in Western Europe of 12% compared to the situation in 1995. We also discerned six measures that improve current packaging by means of

[11] In Ref. [6] the effect of changes in the implementation order is shown for primary packaging.

material substitution. The potential reduction in CO_2 emissions for these measures is calculated at 12% of the CO_2 emissions related to primary packaging in 1995. Finally we discerned seven measures that involve large changes in current packaging practices or require changes in consumer behavior. The potential reduction in CO_2 emissions of these measures might be 16% of the CO_2 emissions in 1995 related to transport packaging. Implementation of these measures would require large changes in current packaging practices or require changes in consumer behavior. It is therefore expected that the difficulty of implementation would be larger than for the other two categories.

Summation of all investigated measures results in a total technical reduction potential of CO_2 emissions related to transport packaging of 40% compared to 1995. The cost-effective potential of CO_2 emission reduction is calculated at 33%. Measures are considered to be cost-effective when the total life cycle costs of the improved package are lower than for the reference package. The reason that many measures are cost-effective (result in lower life cycle costs than in the reference situation) are the large savings in material costs.

This study presents a *first* analysis of the reduction of CO_2 emissions that can be achieved by improved management of material use for transport packaging. Further research should focus on bringing more detail into the calculations to improve the reliability of the results. Possible improvements that will bring more detail into the calculations for primary packaging are (1) the distinction of different regions in Europe, which will affect parameters such as transportation distance, implementation level and production costs, (2) the distinction of more specific packaging categories, which will bring more detail into the improvement options and (3) more specific cost calculations like taking the transaction costs into account. Further research should also focus on improvement options in the long term like new packaging materials as biopolymers. Finally, research that focuses on the barriers of large-scale diffusion of new packaging and possible solutions to overcome these barriers is necessary.

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